

Recoverable DTN Routing based on a Relay of Cyclic Message-Ferries on a MSQ Network

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Abstract—An interrelation between a topological design of network and efficient algorithm on it is important for its applications to communication or transportation systems. In this paper, we propose a design principle for a reliable routing in a store-carry-forward manner based on autonomously moving message-ferries on a special structure of fractal-like network, which consists of a self-similar tiling of equilateral triangles. As a collective adaptive mechanism, the routing is realized by a relay of cyclic message-ferries corresponded to a concatenation of the triangle cycles and using some good properties of the network structure. It is recoverable for local accidents in the hierarchical network structure. Moreover, the design principle is theoretically supported with a calculation method for the optimal service rates of message-ferries derived from a tandem queue model for stochastic processes on a chain of edges in the network. These results obtained from a combination of complex network science and computer science will be useful for developing a resilient network system.

I. INTRODUCTION

A delay/disruption-tolerant network (DTN) routing in a store-carry-forward manner is useful especially for disasters, battlefields, and poor communication environments on mobile devices or ad hoc wireless connections [1], [2], [3]. Even if some connections are removed by failures or attacks, it is expected that a packet is delivered before very long in a DTN routing by re-establishing or re-generating an end-to-end route. There are many protocols in DTN routing methods [1], [2]. We focus on a message-ferries scheme [3] instead of the most trivial approaches by flooding with a lot of redundant messages. In the message-ferries scheme, ferries of communication agents move proactively to send and receive messages, and distributedly give support to the delivery of messages. In the DTN as a collective adaptive system (CAS), it is very important how to design the interactions among message-ferries in what type of moves or actions.

We have proposed the searching and routing methods by message-ferries where actions obey random walks on a fractal-like network [4]. The methods are better than the conventional optimal search by biophysically inspired Lévy flights on a square lattice [5], [6], [7] for homogeneously distributed targets at unknown positions, because the fractal-like network structure is adaptive to the uneven distribution of communication flows between send and receive requests according to spatially inhomogeneous population densities.

However, random walks are predominated by contingency. For a higher reliable DTN routing, we consider a design principle of configuration and autonomous actions with recoverable procedures in CAS. It is based on the cooperation in cyclic moving of message-ferries on the multi-scale quartered (MSQ) network taking into account several advantages of the special fractal-like structure [8], [9]. Moreover, we give an estimation procedure for the optimal service rates of message-ferries from a queueing theory. Thus, we focus on consistent simple ways for a collective (routing) function, theoretical and algorithmic validity, and adaptiveness for a change, which depend on the configuration and actions in CAS.

II. MULTI-SCALE QUARTERED NETWORK

We consider a geographical network construction, in which the spatial distribution of nodes is naturally determined according to population in a self-organized manner. The following MSQ network model is generated by a self-similar tiling of faces for load balancing of communication requests in the territories of nodes. The territory is assigned by the nearest access from each user's position to a node on a geographical map. Note that communication requests are usually more often generated and received at a node whose assigned population is large in the territory, and that the territories of nodes are determined by the nearest access. Thus, how to locate nodes is important for balancing the communication load as even as possible.

[Generation procedure of a MSQ network]

- Step0: Set an initial triangulation of any polygonal region which consists of equilateral triangles.
- Step1: At each time $1, 2, 3, \dots$, a triangle face is chosen with a probability proportional to the population in the space.
- Step2: As shown in Fig. 1, four smaller equilateral triangles are created from the subdivision by adding three nodes, at the intermediate point of each edge of the chosen triangle, respectively.
- Step3: Return to Step 1, while the network size (the total number of nodes) does not exceed a given size.

Since a step-by-step selection of triangle face is unnecessary in the above algorithm, the subdivision process can be initiated in an asynchronously distributed manner, e.g. according to the increase of communication requests in an individual triangle

area. We will discuss why the configuration of equilateral triangles is better in the next section. On a combination of complex network science and computer science approaches, this model has several advantages [8], [9]: the robustness of connectivity without vulnerable high degree nodes, the bounded short distance path between any two nodes, and the efficient decentralized routing on a planar graph which tends to be avoided from interference among wireless beams. Complex network science that emerges at the beginning of the 21st century provides a new paradigm of network self-organization, e.g. based on recursive growing geometric rule for the division of a face [10], [11], [12], [13] or for the attachment which aims at a chosen edge [14], [15], [16] in a random or hierarchical selection. These self-organized networks including the MSQ network have a potential to be superior to the vulnerable scale-free network structure found in many real network systems [17], [18], such as Internet, WWW, power-grids, airline networks, etc.

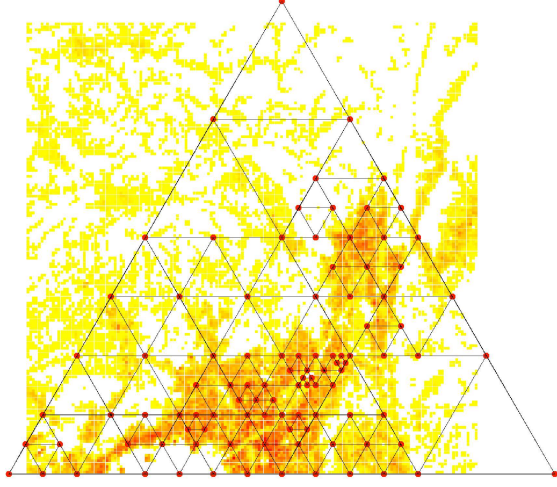


Fig. 1. Example of MSQ network generated by the subdivision of equilateral triangles on a geographical map. From white, yellow, to orange, the gradation is proportional to the population density.

III. RELIABLE MESSAGE-FERRIES ROUTING

A. An efficient DTN routing

We preliminarily explain some basic elements and mechanisms to realize a message-ferries routing on a planar network. Figure 2 shows the forward direction of each edge defined by the clockwise cycles on upper triangles and the counterclockwise cycles on lower triangles. In order to reduce the number of assignment of a direction to each edge, we omit the assignment for the center faces of triangles at any layer. The layer is defined by a depth of quartered triangle faces (or by the number of the recursive divisions) from an initial outermost triangle. The backward direction of edge is defined in the same way by changing each of cycle to the opposite direction. We remark that a cycle is corresponded to three edges on the triangle face. Moreover, these cycles represent the delivery routes of message-ferries. We consider another idea as shown

in Fig. 3: each triangle face is directed by only clockwise cycles. Then, both forward and backward directions of an edge are assigned without counterclockwise cycles, except the edges of the outermost triangle. The better case of either Fig. 2 or 3 depends on situations of the utilization in what type of communication resource and environment is given.

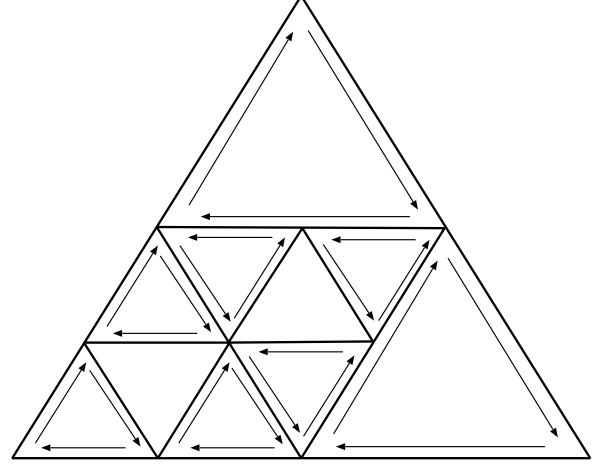


Fig. 2. Cycles on equilateral triangle faces in a MSQ network with the 1st and 2nd layers, which consist of large and small triangles, respectively.

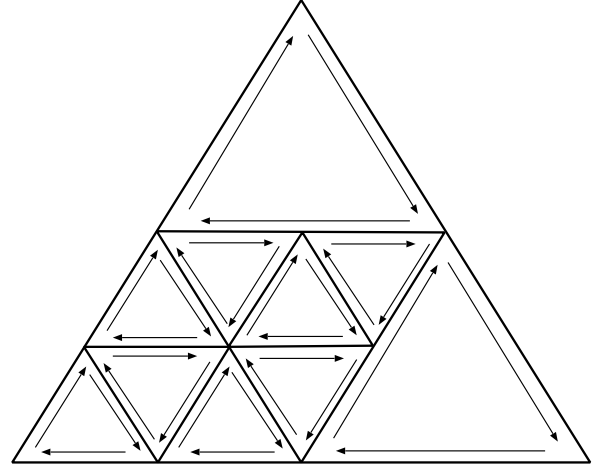


Fig. 3. Another idea of directional edges defined by only clockwise cycles.

We consider the autonomous distributed delivery processes after a communication request is occurred at a source node. In a store-carry-forward manner, a ferry that visits the source node s picks up a data from s , and carries it to the next mediator node on the routing path, which is found by a routing algorithm as mentioned later. The mediator node stores the data into its queue. Here, the pickup and store times are ignored. Then, any other ferry that visits the 1st mediator node picks up the data, and carries it to the 2nd mediator node. Such relaying by ferries are repeated until a ferry reaches at the terminal node t and the data is delivered. We assume that each ferry autonomously moves on a triangle cycle at a turnaround rate. Several ferries exist on a cycle at random

interval each other, and may have various speeds. Therefore, in the random process by heterogeneous message-ferries, similar pickup and carry services are available at any time. This property of the random process rationalizes an exponential distribution of service times in the next subsection. In this routing, direct interactions between ferries at a time are not necessary, because a node act as the helper to temporarily store and forward a data asynchronously with ferry's encounters. Note that our approach is categorized as multi-route and node relaying type in the ferry route design algorithms [3]. Although the message ferries act just like information frames in Token Ring [19] at the data-link layer, it is quite different that the special topology of MSQ network generated by subdivision of equilateral triangles is focused therefore a relay of data transfers on cycles by mobile agents can be performed as a routing.

Since the MSQ networks that consist of squares and equilateral triangles belong to planner graphs with the $t = 2$ -spanner property [9], [20], we can apply an efficient adaptive face routing algorithm [21], [22] in order to find a shortest distance path between any two node. The spanner property means that a length of path measured by the sum of link lengths on the path as Euclidean distances is bounded at most the twice of the straight line between two nodes. Efficiently, the routing algorithm uses only local information about the edges of faces that intersects the straight line between source s and terminal t nodes, and the nodes of the faces are restricted in the ellipsoid whose chord length is defined by twice of the $s-t$ line as shown in Fig. 4. We remark that the routing path can be represented by a concatenation of triangle cycles for the intersected faces with the $s-t$ line. If there are several shortest distance paths with a same path length between two nodes, e.g. due to symmetry, each of the paths is equally selected at random with the rate $1/(\text{the number of the paths}) \times (\text{the amount of communication flows between the nodes})$. Figure 5 shows that the routing algorithm is able to find an alternative path when some edges are disconnected, although a greedy forwarding policy based on the distance from the neighbor of a current node to the terminal node supports the path finding in the parts of removed edges and the corresponding triangle faces. The dashed piecewise linear line denotes the shortest distance path in this case, and the dotted piecewise linear line denotes the original path. Thus, even with several damages for the network, the routing can be performed in a connected part before the fully destruction. In addition, the path finding is able to be performed reactively on-demand after a communication request occurs, and therefore adaptive for changes of connections.

B. Optimal service rates of message-ferries

We naturally assume that the occurrence of communication request is independent random event, but the amount is proportional to a product of populations around source and terminal nodes, and that the service to transfer the request is stochastic in a multihop manner by passing through mediator nodes on a network. Thus, we apply a queueing model to the

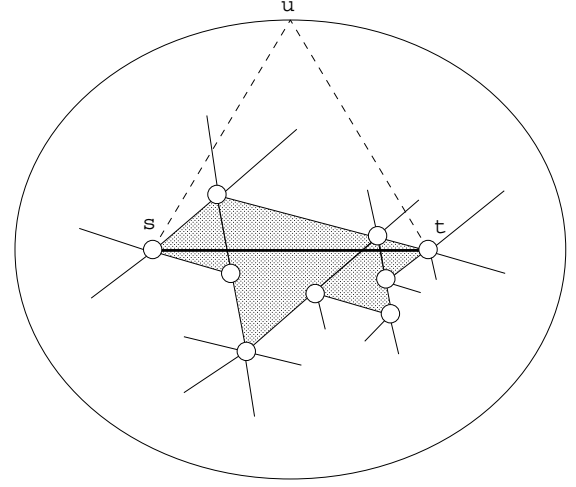


Fig. 4. Local search area in the ellipsoid with focus points s and t for the adaptive face routing. The chord length that consists of $s-u$ and $u-t$ is defined by the twice of $s-t$ line because of $t = 2$ -spanner.

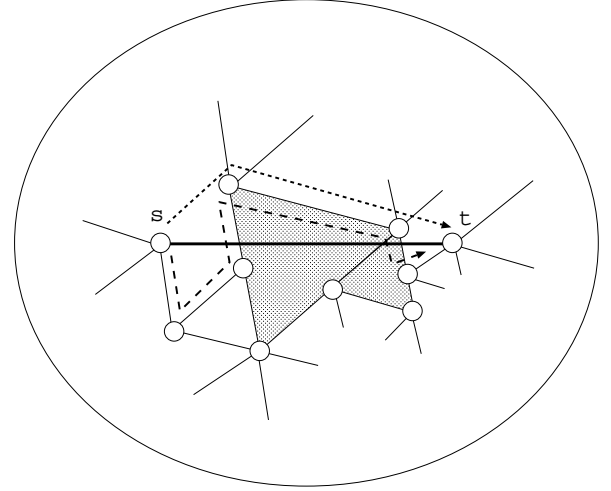


Fig. 5. Detour case in disconnections.

communication flows as follows.

For the M/M/1 queue system [23] as Kendall notation with the arrival rate λ according to a Poisson process and the service rate μ in an exponential distribution, the average number of remaining requests is

$$L = \frac{\rho}{1 - \rho}, \quad \rho \stackrel{\text{def}}{=} \frac{\lambda}{\mu},$$

and the average end-to-end delay is

$$E(T) = \frac{L}{\lambda} = \frac{1}{\mu - \lambda}. \quad (1)$$

When we consider such stochastic processes on a network, the tandem queue model in Fig. 6 is applied. Each path between source and terminal nodes (e.g. in Fig. 7) is decomposed into chained edges corresponded to M/M/1 queues. In the tandem queue model, from Burke's theorem, these queues are independent of each other in a Poisson process. Then, the

average end-to-end delay in a direction is given by the sum of ether

$$\frac{1}{\mu_l^f - \lambda_l^f(k)} \quad \text{or} \quad \frac{1}{\mu_l^b - \lambda_l^b(k)}$$

in Eq.(1), where $\lambda_l^f(k)$ denotes the arrival rate for the sum of flows passing through an edge corresponded to the l -th cycle of message-ferry, the superscript f and b denote the forward and the backward directions of edge, the index number $k = 1, 2, 3$ is due to the one-to-three corresponding between a cycle and three edges of triangle. If two cycles get involved in a same direction on an edge with respect to both adjacent sides of faces, the arrival rate $\lambda_l^f(k)$ per cycle is given by (the sum of flows)/2. We assume $\lambda_l^f(k) = \lambda_l^b(k)$ by the symmetry of flows to simplify the discussion. The amount of flows on an edge is corresponded to the link load called as routing betweenness centrality [24]. The service rate μ_l^f corresponds to the turnaround rate of the l -th cycle of message-ferry whose direction of clockwise or counterclockwise is determined by the coincidence with the forward direction of edge on the triangle cycle (see Fig. 2). On each cycle, the condition

$$\mu_l^f > \max\{\lambda_l^f(1), \lambda_l^f(2), \lambda_l^f(3)\}, \quad (2)$$

is necessary for the stable situation without involving ∞ -length queue.

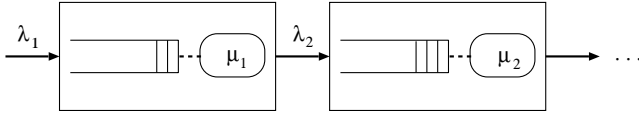


Fig. 6. Tandem queue model for a path. The average end-to-end delay is given by $\sum_i \frac{1}{\mu_i - \lambda_i}$.

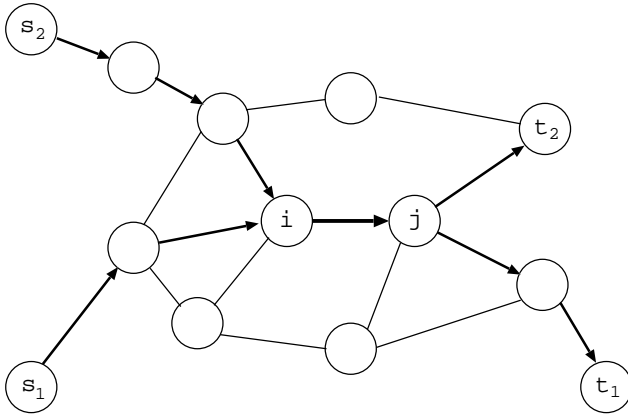


Fig. 7. Communication flows for an edge $i-j$ on two paths. Here, s_1 and s_2 denote source nodes, t_1 and t_2 denote terminal nodes. The edge $i-j$ receives the directional flows superimposed by the amounts passing through the edge for paths $s_1 \rightarrow t_1$, $s_2 \rightarrow t_2$, and so on.

We consider the delivery cost C that consists of the end-to-

end delay and the service load.

$$\sum_{i,j} \sum_{l \in \text{path}(i,j)} \left(\frac{1}{\mu_l^f - \lambda_l^f(1)} \oplus \frac{1}{\mu_l^f - \lambda_l^f(2)} \oplus \frac{1}{\mu_l^f - \lambda_l^f(3)} \oplus \frac{1}{\mu_l^b - \lambda_l^b(1)} \oplus \frac{1}{\mu_l^b - \lambda_l^b(2)} \oplus \frac{1}{\mu_l^b - \lambda_l^b(3)} \right) + \sum_{l=1}^{N_l} (\mu_l^f + \mu_l^b), \quad (3)$$

where N_l denotes the total number of cycles, \oplus is an exclusive addition operator: one of $\lambda_l^f(1)$, $\lambda_l^f(2)$, $\lambda_l^f(3)$, $\lambda_l^b(1)$, $\lambda_l^b(2)$, $\lambda_l^b(3)$, is chosen for the l -th cycle on $\text{path}(i, j)$ with the corresponding μ_l^f or μ_l^b , and $\text{path}(i, j)$ denotes a set of cycles with respect to the edges of forward or backward direction on the routing path between nodes i and j . There are trade-off relations between the 1st & 2nd rows of the end-to-end delay and the 3rd row of the service load in Eq. (3) for minimizing the delivery cost C . Eq. (3) is rewritten to the sum of cycle-based components

$$\sum_{l=1}^{N_l} \left(\sum_{k=1}^3 \left(\frac{w_l^f(k)}{\mu_l^f - \lambda_l^f(k)} + \frac{w_l^b(k)}{\mu_l^b - \lambda_l^b(k)} \right) + \mu_l^f + \mu_l^b \right),$$

where $w_l^f(1)$, $w_l^f(2)$, $w_l^f(3)$, $w_l^b(1)$, $w_l^b(2)$, $w_l^b(3)$, are the weights obtained from the deformation of Eq. (3).

We can solve the optimal problem for minimizing the object function of Eq.(3) by using the Newton-Raphson method, since the finding at $\partial C / \partial \mu_l^f = 0$ (or $\partial C / \partial \mu_l^b = 0$) results in a one-dimensional search for each variable μ_l^f or μ_l^b . We remark that the solution of

$$\begin{aligned} \frac{\partial}{\partial \mu_l^f} \left(\frac{w_l^f(k)}{\mu_l^f - \lambda_l^f(k)} + \mu_l^f \right) \\ = \frac{-w_l^f(k)}{(\mu_l^f - \lambda_l^f(k))^2} + 1 = 0, \end{aligned}$$

is given by $\mu_l^f = \sqrt{w_l^f(k)} + \lambda_l^f(k)$. Thus, for minimizing the cost C of Eq.(3), it is useful that the initial value is set as

$$\mu_l^f = \sqrt{w_l^f(k')} + \max\{\lambda_l^f(1), \lambda_l^f(2), \lambda_l^f(3)\}, \quad (4)$$

considering the condition (2). k' denotes $\text{argmax}\{\lambda_l^f(k)\}$. Since a triangle has the minimum number of edges to form a polygonal cycle, only three variables $\lambda_l^f(1)$, $\lambda_l^f(2)$, and $\lambda_l^f(3)$ affect to the optimal solution of μ_l^f . If we consider the proposed scheme of message-ferries routing to any other shaped cycles with more than three edges, such as on squares, on chair or sphinx type polygons [9], the tuning of service rates will be more constrained than the triplets in the maximum of Eq. (4) for minimizing the cost C of Eq.(3). Thus, the triangle cycle is the best choice. In the above discussion, the case of backward direction is similarly treated by replacing the superscript from f to b .

IV. TO BE PERSISTENT LIVING SYSTEM

A. Adaptive recovery for local accidents

We have two strategies of ferry initiation and node initiation with monitoring and controlling of the system state for a recovery in local accidents. These situations are illustrated in Figs. 8 and 9. In the following, although we explain the procedures for the clockwise cycles in the case of Fig. 2, the same ways can be applied for the counterclockwise cycles and for the case of Fig. 3. When a white square node falls into malfunction and becomes non-interactive with a ferry, each of the related three ferries detects it in some turnarounds, and moves to the next neighbor black circle node beyond the removed white square node, as shown in Fig. 8. Then, their ferries begin to move on the larger cycle.

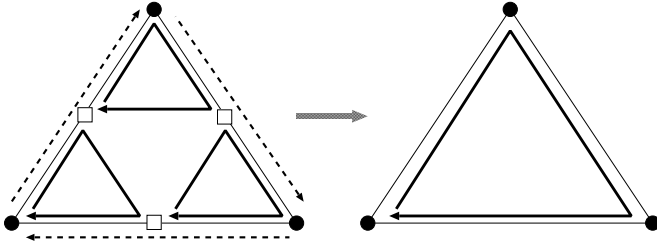


Fig. 8. Recovery procedure from (left) to (right) for a node's accident denoted by white square. Dashed arrow line shows the move of ferry in changing from each cyclic route of bold arrow line to the larger unified one.

When a ferry encounters an accident and stop the moving, the black circle nodes that detect it from non-visiting of ferry in a time-interval notify the next neighbor black square nodes to initiate the recovery process, as shown in Fig. 9. Each of the notified black square nodes negotiates with the moving ferries on the cycles of small triangles, then a new cycle of the larger triangle is created by changing the cyclic routes for the ferries. In deeper layers, the recover process is similarly performed as shown in Fig. 10. The gray square node in Fig. 10 detects non-visiting of ferry after changing the cyclic route, and becomes inactive. Thus, if an accident occurs at a shallow layer, the procedures are hierarchically propagated to deeper layers.

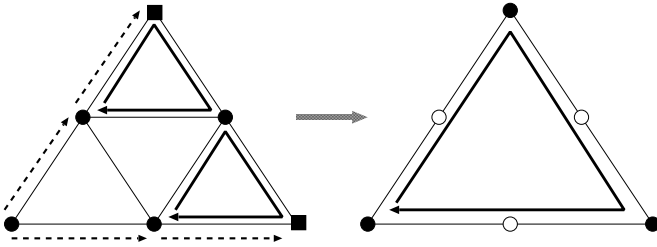


Fig. 9. Recovery procedure from (left) to (right) for a ferry's accident at the bottom left triangle. Dashed arrow line shows the notification among nodes. Bold arrow line shows the ferry's cyclic route. White circle represents that the node becomes inactive.

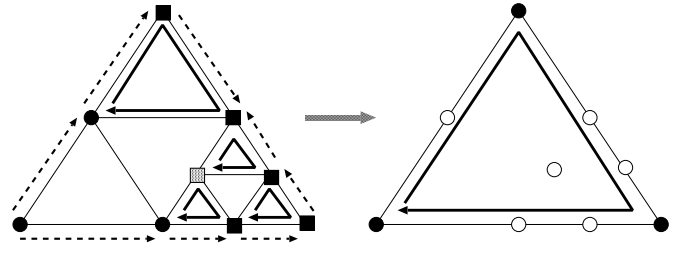


Fig. 10. Recovery procedure from (left) to (right) with hierarchical propagation for a ferry's accident at the bottom left triangle. Dashed arrow line shows the notification among nodes. Bold arrow line shows the ferry's cyclic route. White circle represents that the node becomes inactive.

B. Update of cyclic paths in the growth

On the other hand, we consider the following procedures, when new nodes are added by subdivision of triangle face in order to be a persistent living system for the growing MSQ network and the message-ferries routing on it. After detecting the addition of nodes by ferries, these ferries negotiate with the new nodes to move on one of the smaller cycles, as shown in Fig. 11. Such procedures can be performed at any layers of triangle faces and even simultaneously in some distant parts.

The update process is used to the hierarchical recovery for a ferry's accident, when nodes work correctly. The white inactive nodes on the 2nd layer at the right of Fig. 10 act same as adding new nodes at the left of Fig. 11, then the related message-ferries negotiate with these nodes to move on smaller cycles at the right of Fig. 11. After the change of routes, the inactive nodes on the 3rd layer begin to return the state in a right-down triangles at the right of Fig. 10. These procedures propagate to deeper layers hierarchically with the unification and division of ferry's routes from transiently resetting and re-creating the cycles on the layers back to the damaged layer by the accident, as shown in Fig. 12. The resetting and re-creating seem to be wasteful, however using such consistent simple ways is better especially for unpredictable situation in maintaining the minimum performance. Because extremely complex procedures and controls can be avoided.

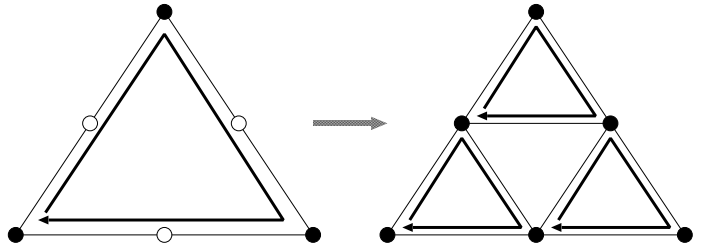


Fig. 11. Update procedure from (left) to (right) by subdivision of triangle face in the network growth. Bold arrow line shows the ferry's cyclic route. From white to black circle, the added node becomes active.

V. CONCLUSION

We have proposed a design principle in CAS for a DTN routing based on autonomously moving message-ferries on a special structure of MSQ network self-organized by iterative

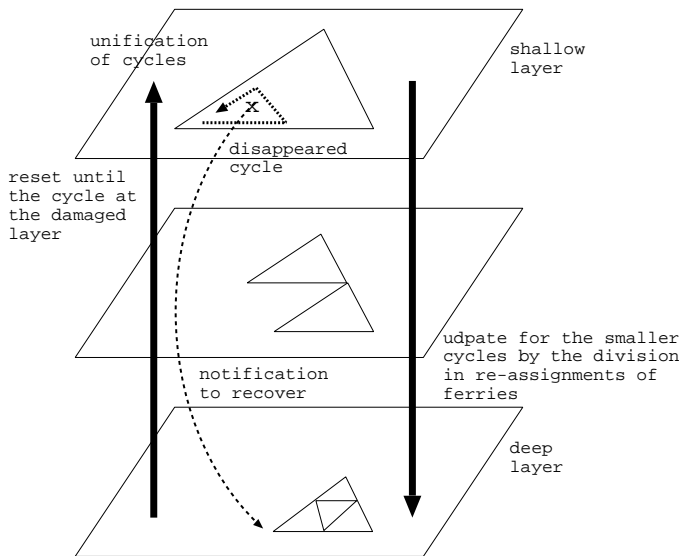


Fig. 12. Unification and re-division of triangle cycles.

subdivision of faces. In the subdivision, nodes are located as balancing the amount of communication requests as possible which requests are generated or received at a node according to population in its territory defined by the nearest access. By considering the correspondence between each cycle on a triangle and a moving of message-ferry, we realize a reliable and efficient message-ferries routing. In the routing, a relay of cyclic message-ferries, the bounded path length by the t -spanner property, and the adaptive face routing algorithm are key factors. As stochastic processes, we have considered the arrival of communication request and the service of transfer in the relay of cyclic message-ferries. The tandem queue model in a queueing theory is applied for this problem setting. We have derived a calculation method of the optimal solution for minimizing the delivery cost defined by a sum of the end-to-end delay and the service load in a trade-off relation. Moreover, we have considered recovery procedures for local accidents, and update procedures of ferry's cyclic routes in an incremental growth of MSQ network. These collective adaptive configuration and procedures will be evaluated in numerical simulations for more detailed design.

We mention some further studies. Our proposed method can be applied to a transport logistic system (e.g. including by vehicles or small flying devices) in both normal and emergent situations on a wide area. However, how to define a processing unit of communication or transportation requests is an issue. In addition, temporal disconnecting cases at simultaneous and many parts may be discussed by extending our approach in considering disaster situations. These challenges will be useful for developing a resilient network as CAS in theoretical and practical points of views [25], [26].

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